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14. ABSTRACT

Military information collected from streaming video of real-time unmanned aerial reconnaissance, battlefield operations or from multi-spectral satellite imagery, for example, requires intelligent processing by analysts to reduce response time and increase accuracy of interpretation. This research concerns the understanding of, i.e., modeling and classifying of, information in data. Of primary focus has been development of new algorithms for processing large data sets. In particular the proposed techniques emphasize exploiting all available data rather than reducing the data before processing. We have made fundamental progress in the classification problem via encoding sets of images as points on parameter spaces as well as in the model fitting problem using radial basis functions that represent geometry in data.

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GEOMETRIC, ALGEBRAIC AND TOPOLOGICAL STRUCTURE FOR SIGNAL AND IMAGE PROCESSING

AFOSR GRANT FA9550-04-1-0094
FINAL REPORT
PRINCIPAL INVESTIGATOR: MICHAEL KIRBY
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1. Objectives. Military information collected from streaming video of real-time unmanned aerial reconnaissance, battlefield operations or from multi-spectral satellite imagery, for example, require intelligent processing by analysts to reduce response time and increase accuracy of interpretation. As the National Defense becomes increasingly dependent on evaluation of data produced by state-of-the art technology it is a matter of critical strategic importance to develop the associated basic mathematical theory to assist in high data rate information processing and analysis.

In addition to exploitable statistical features, signals and images possess information, or mathematical coherent structure reflected, for example, by the existence of low-dimensional manifolds. This work concerns the development of a range of fundamental mathematically based techniques drawing from algebra, geometry and topology that will be applied to efficiently represent, process and analyze a wide range of data sources under varying conditions to ultimately provide a better understanding of the data content.

2. Final Status of Effort. Below we highlight some of the main achievements of the research.

2.1. Recognition of Human Faces at Ultra Low-Resolution. Recent work has established that digital images of a human face, collected under various illumination conditions, contain discriminatory information that can be used in classification. In this paper we demonstrate that sufficient discriminatory information persists at ultra- low resolution to enable a computer to recognize specific human faces in settings beyond human capabilities. For instance, we utilized the Haar wavelet to modify a collection of images to emulate pictures from a 25- pixel camera. From these modified images, a low-resolution illumination space was constructed for each individual in the CMU-PIE database. Each illumination space was then interpreted as a point on a Grassmann manifold. Classification that exploited the geometry on this manifold yielded error-free classification rates for this data set. This suggests the general utility of a low-resolution illumination camera for set-based image recognition problems.

2.2. Principal Angles Separate Subject Illumination Spaces. The theory of illumination cones is well developed, and has been tested extensively on the Yale Face Database B (YDB) and CMU-PIE (PIE) data sets. This paper shows that if face recognition under varying illumination is cast as a problem of matching sets of images to sets of images, then the minimal principal angle between subspaces is sufficient to perfectly separate matching pairs of image sets from non-matching pairs of image sets sampled from YDB and PIE. This is true even for subspaces estimated from as few as six images, and when one of the subspaces is estimated from as few as three images, if the second subspace is estimated from a larger set (ten or more). This suggests the variation under illumination may be thought of as useful discriminating information rather than unwanted noise.

2.3. Examples of Set-to-Set Image Classification. Our initial attraction to the set-to-set paradigm arose in the multi-class problem where the sets where generated by varying illumination over a person. We also found that different types of sets also afforded interesting classification results. For example, a collection of images of dogs can be compared to a collection of images of cats. We found that the label of a set of images, i.e., whether the set consisted of dogs or cats could be determined with high reliability. Further experiments showed that the gender of a set of images (the images would either be all female or all male) could also be determined with high reliability. This research is being extended to images provided by the forest service where they are interested in whether the set consists of managed or non-managed forests.

2.4. Variations in Pose and Illumination. We present a face recognition method using multiple images where pose and illumination are uncontrolled. The set-to-set framework can be utilized whenever multiple images are available for both gallery and probe subjects. We can then transform the set-to-set classification problem as a geometric one by realizing the linear span of the images in a given resolution as a point on the Grassmann manifold where various metrics can be used to quantify the closeness of the identities. Contrary to a common practice, we will not normalize for variations in pose and illumination, hence showing the effectiveness of the set-to-set method when the classification is done on the Grassmann manifold. This algorithm exploits the geometry of the data set such that no training phase is required and may be executed in parallel across large data sets. We present empirical results of this algorithm on the CMUPIE Database and the Extended Yale Face Database B, each consisting of 67 and 28 subjects, respectively.

2.5. Short Time Principal Component Analysis. Experiments demonstrated that EEG representations based on short-time PCA can be classified by simple linear discriminant analysis (LDA) with an accuracy of about 80the sensitivity of this result to the values of the representation parameters suggests that time-embedding is necessary for good performance and that the discriminatory information is not isolated to a small number of basis vectors. Analysis of the classifiers weights revealed that short-time PCA basis vectors late in the sequence play significant roles, suggesting that the low-variance activity represented by these vectors is strongly related to the mental task. This hypothesis warrants further study. Information gleaned from analyses can be used to select subsets of features to greatly reduce the dimensionality of the data and possibly improve the generalization performance of the classifiers. Extending this analysis to consider the time course of significant electrodes and basis vector directions could lead to hypotheses of the underlying cognitive activity.

2.6. A Pseudo-Isometric Embedding Algorithm. We present a new Whitney like algorithm for finding a low dimensional pseudoisometric embedding of a sampled Riemannian manifold. Tangent spaces on the manifold are estimated from the data and then projected using a criterion that ensures optimal smoothness of the inverse. This short projection is not isometric but can be made to be approximately isometric by determining an appropriate global lengthening transformation in the embedded space. We illustrate the application of this algorithm on numerically obtained solutions of the Kuramoto-Sivashinksy partial differential equation.

2.7. Mapping the Identity for Classification in Nonlinear Spaces. Constructing functions from data for mapping the identity provides a natural means for

performing classification in high dimensions. We illustrate this idea with the application of the multivariate state estimation technique (MSET) a method normally considered in the context of failure prediction and fault detection. This approach provides a fast alternative to other approaches that depend on nonlinear optimization algorithms such as nonlinear bottleneck neural networks. We propose the application of MSET to the image or video classification problem and present the results of a face recognition experiment under variations in illumination.

3. Summary of Accomplishments. Over the course of this award twenty papers were written, nine talks were presented and eight disclosures were made resulting in three patent applications.

4. Personnel Supported. The following personnel were supported by this award:

- Michael Kirby, PI.
- Silvia Osnaga, Graduate Research Assistantship.
- Arta Jamshidi, Graduate Research Assistantship. He is scheduled to graduate in spring 2008.

5. Technical Publications. Over the period of the grant twenty papers were written 14 of which have appeared and 6 of which are submitted.

1. A. Jamshidi and M. Kirby, *Skew Radial Basis Functions*, submitted 2007.
2. Yui Man Lui and J. Ross Beveridge and Bruce A. Draper and Michael Kirby, *Image-Set Matching using Canonical Correlation Analysis*, submitted 2007.
3. J.R. Beveridge, Jen-Mei Chang, Michael Kirby, and Chris Peterson, *Feature Patch Illumination Spaces and Karcher Compression for Face Recognition via Grassmannians*, submitted 2007.
4. J.R. Beveridge, Bruce Draper, Jen-Mei Chang, Michael Kirby, Holger Kley and Chris Peterson, *Principal Angles Separate Subject Illumination Spaces in YDB and CMU-PIE*, (submitted 2007).
5. David W. Dreisigmeyer and Michael Kirby, A Pseudo-Isometric Embedding Algorithm (submitted 2007).
6. David W. Dreisigmeyer and Michael Kirby, *Mapping the Identity for Classification in Nonlinear Spaces*, (submitted 2007).
7. Jen-Mei Chang, M. Kirby, H. Kley and C. Peterson, R. Beveridge, B. Draper, *Recognition of Digital Images of the Human Face at Ultra Low Resolution via Illumination Spaces*, In ACCV '07, part 2 (8^{th} Asian Conference on Computer Vision, Tokyo, Japan) in Springer Lecture Notes in Computer Science, Vol. 4844, pg 733-743, (2007).
8. Jen-Mei Chang, Michael Kirby and Chris Peterson, *Set-to-Set Face Recognition Under Variations in Pose and Illumination*, 2007 Biometrics Symposium, Baltimore, MD, September, 2007.
9. A. Jamshidi and M. Kirby, *A spatio-temporal criterion for automatic model order determination,* SIAM Journal of Scientific Computing, Vol. 29, 941, May, 2007.
10. Jen-Mei Chang, Michael Kirby, Holger Kley, Chris Peterson, J.R. Beveridge and Bruce Draper, *Examples of Set-to-Set Image Classification*, In: Seventh International Conference on Mathematics in Signal Processing Conference Digest, The Royal Agricultural College, Cirencester, Institute for Mathematics and its Applications, December, 2006, pp. 102–105.
11. Yue Qiao, Larry Ernst and M. Kirby, *Developing a Computational Radial*

Basis Function (RBF) Architecture for Nonlinear Scattered Color Data, Proceedings NIP22 International Conference on Digital Printing Technologies, Sept. 2006.

12. C. Anderson, M. Kirby, J.N. Knight, Classification of Time Embedded EEG Using Short Time Principal Component Analysis, (Book Chapter to appear) In Towards Brain Computer Interfacing, edited by G. Dornhege, J. del R. Millan, T. Hinterberger, D.J. McFarland, and K.R. Müller, The MIT Press, 2006.
13. J.M. Chang, R. Beveridge, B. Draper, M. Kirby, H. Kley and C. Peterson, *Illumination Face Spaces are Idiosyncratic*, IPCV'06, Vol 2., 390-396, 2006, CSREA Press.
14. Anderson, C.W., Knight, J.N., O'Connor, T., Kirby, M.J., and Sokolov, A. (2006) Geomeric Subspace Methods and Time-Delay Embedding for EEG Artifact Removal and Classification, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 14, no. 2, pp. 142–146, June 2006.
15. A. A. Jamshidi and M. J. Kirby, *Examples of Compactly Supported Functions for Radial Basis Approximations*, Proceedings of The 2006 International Conference on Machine learning; Models, Technologies and Applications, Editors H. R. Arabnia, E. Kozerenko and S. Shaumy, 155-160, 2006.
16. Anderson, C.W., Knight, J.N., Kirby, M.J. (2005) An Inexpensive Brain-Computer Interface Based on Spatial and Temporal Analysis of EEG. Proceedings of HCI International, (HCI-I) 2005, Las Vegas, NV, (CD-ROM).
17. David A. Peterson, James N. Knight, Michael J. Kirby, Charles W. Anderson and Michael H. Thaut, Feature selection and blind source separation in an EEG-based brain-computer interface, EURASIP Journal on Applied Signal Processing, vol. 2005, issue 19, pp. 3128-3140.
18. D. Broomhead and M. Kirby, *Large Dimensionality Reduction using Secant-based Projection Methods: The Induced Dynamics in Projected Systems*, Nonlinear Dynamics 41(1-3) (August 2005), pp. 47-67.
19. M. Kirby, Nonlinear Signal Processing, Encyclopedia of Nonlinear Science, ed. Alwyn Scott. New York and London: Routledge, 2004.
20. A. Fox, M. Kirby, M. Montgomery, J. Persing, A Comparison of Optimal Low Dimensional Projections of a Hurricane Simulation. In: Dynamics and Bifurcation of Patterns in Dissipative Systems, G. Dangelmayr and I. Oprea (eds.), World Scientific Series on Nonlinear Science, Vol. 12, pages 292-308, World Scientific, Singapore, 2004

6. Interactions/Transitions.

6.1. Presentations. Over the course of the award nine presentations of the results of this project were made. The UCLA workshop invited 40 experts to present lectures to a large audience over a one week period.

1. *Some Mathematical Ideas for Attacking the Brain Computer Interface Problem*, 3rd Annual Intermountain/Southwest Conference on Industrial and Interdisciplinary Mathematics, Arizona State University, February 2004.
2. *Dimensionality Reduction using Secant-based Projection Methods*, MGA Workshop III: Multiscale structures in the analysis of High-Dimensional Data, IPAM, UCLA October 2004.
3. *Reduction of Dynamical Systems using Secant-based Projection Methods: The Induced Dynamics in Projected Systems*, IMA Signal Processing Conference 2004, Cirencester, UK.
4. *Face Recognition*, ISTEC Symposium, Colorado State University, 2005.
5. *New Techniques and Results for the Brain Computer Interface Problem*, Invited Plenary Talk, AFOSR Image Processing Review, University of North Carolina State, May, 2005.
6. *Discrete and Continuous Wavelet Analysis for Multiscale Ecological Analysis*, PRIMES Lecture and Lab Module, Colorado State University, January, 2006.
7. *Examples of Set-to-Set Face Recognition*, Conference on Mathematics in Signal Processing, Institute for Mathematics and its Applications, Royal Agricultural College, Cirencester, U.K., December 2006.
8. *Some Open Problems in the Analysis of Large Data Sets*, Workshop on New Directions in Complex Data Analysis, Breckenridge, CO, 3/07.
9. *Pattern Recognition Using Sets of Observations*, AFOSR Sensing Program Review, Harvard University 6/07.

6.2. Transitions. Related activities that benefit from this effort. The MSPA-MCS NSF award is particularly noteworthy as it permitted an expansion of the collaboration to include faculty from the Department of Computer Science at Colorado State University.

1. CO-Principal Investigator,*CMG: Analysis of Transport, Mixing, and Coherent Structures in Hurricane Intensity*, NSF ATM-530884, Funding 10/1/05–9/30/09, $1,570,000.
2. Principal Investigator, National Science Foundation MSPA-MCS: New Tools for Algebro-Geometric Data Analysis, PI, $500,000, 8/15/2004–7/31/2007.
3. Principal Investigator, *Mutliscale Analysis of Vegetation Disease*, United States Forest Service, 8/16/04-7/31/05, $15,000.
4. Principal Investigator, *Face Manifolds for Recognition*, Directorate of Central Intelligence, NMA501-03-BAA-0001
5. CO-Principal Investigator,*Geometric Pattern Analysis and Mental Task Design for a Brain-Computer Interface*, NSF IIS-0208958

7. Patents and Disclosures. The PI was involved with a number of patents and disclosures over the courses of this project including:

1. M. Kirby and Yue Qiao (2004), *Apparatus, System and Method for Interpolating High-Dimensional Non-linear Data*, Patent application IBM Docket No.:BLD920040032US1
2. Michael Kirby, Jen-Mei Chang, Holger Kley, Chris Peterson, J.R. Beveridge and Bruce Draper, *Set-to-Set Pattern Classification*, Patent filed 8/2007.

3. Michael Kirby and Arta Jamshidi, *Nonlinear Function Approximation over High Dimensional Domains*, Patent filed 9/2007.
4. M. Kirby and Yue Qiao (2004), *Apparatus, System and Method for Interpolating High-Dimensional Non-linear Data*, U.S. Patent Serial No. 11/263,740 Nov. 1, 2005
5. M. Kirby and A. Jamshidi, *A New Method for Automatic Order Determination of Radial Basis Function Models*, U.S. Provisional Patent Application, Express Mail EQ 982753865
6. M. Kirby, *Adaptive Nonlinear Compression Algorithm for Modeling and Prediction*, U.S. Provisional Patent Application, Express Mail EQ 982753874
7. M. Kirby, R. Beveridge, V. Chang, B. Draper, H. Kley and C. Peterson, *A Low Resolution Grassmannian Camera for Object Recognition*, CSURF disclosure 06-036, 5/2006.
8. M. Kirby and C. Peterson, *Super High Resolution Biometric Algorithms*, CSURF Disclosure 8/06.
9. M Kirby and D. Dreisigmeyer, Multivariate State Estimation Technique for pattern recognition and multi-class image classification. 2/07

8. Honors.

- Nominated for Preston Davis Award for Instructional Innovation.
- Nominated for College of Natural Sciences Professor Laureate.